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AN EVALUATION OF CRYOGENIC
VACUUM SYSTEM DESIGN PARAMETERS
CHARLES E. DOUGHERTY

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AN EVALUATION OF CRYOGENIC
VACUUM SYSTEM DESIGN PARAMETERS

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Charles E. Dougherty

AN EVALUATION OF CRYOGENIC
VACUUM SYSTEM DESIGN PARAMETERS

by

Charles E. Dougherty

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

United States Naval Postgraduate School
Monterey, California

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AN EVALUATION OF CRYOGENIC
VACUUM SYSTEM DESIGN PARAMETERS

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This work is accepted as fulfilling
the thesis requirements for the degree of

MASTER OF SCIENCE

IN

MECHANICAL ENGINEERING

from the

United States Naval Postgraduate School

ABSTRACT

Concepts drawn from the kinetic theory of gases have been utilized to examine basic phenomena associated with cryopumping and low density flow. Relationships based on conductance have been used to examine the significance and interdependence of basic design parameters such as pressure, mass in-leakage rate, shielding, geometrical considerations, and flow regime. Considerations involved in predicting transition flow regime behavior are also discussed.

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TABLE OF CONTENTS

Section	Title	Page
1.	Introduction	1
2.	Kinetic Theory	2
3.	Evaporation and Condensation	5
4.	Flow Regime	7
5.	Conductance	9
	(a) Molecular Flow	10
	(b) Viscous Flow	11
	(c) Transition Flow	12
	(d) Cryosurface Conductance	15
6.	Discussion of Parameters Influencing Cryogenic Vacuum System Design	17
7.	Conclusions	22
Bibilography		23
Appendices		
I.	Illustrations	26
II.	Glossary	34

TABLE OF SYMBOLS

A	surface	cm^2
d	tube diameter, $2r$	cm
F	conductance	$\text{cm}^3 \cdot \text{sec}^{-1}$
f	Maxwell's reflection coefficient	dimensionless
G	mass flow rate	$\text{gm} \cdot \text{sec}^{-1}$
K	Clausing's factor	dimensionless
L	length	cm
M	molecular mass	$\text{gm} \cdot \text{g-mole}^{-1}$
N	molecule flow rate	sec^{-1}
n	number of molecules per unit volume	cm^{-3}
P	pressure	microns Hg
Q	flow rate parameter (product of volumetric flow rate across a plane and the pressure at which it is measured).	$\text{micron} \cdot \text{cm}^3 \cdot \text{sec}^{-1}$
R_o	universal gas constant	$\text{micro} \cdot \text{cm}^3 \cdot \text{deg}^{-1} \text{K} \cdot \text{g-mole}^{-1}$
T	temperature	degrees K
t	time	sec
U	speed	$\text{cm} \cdot \text{sec}^{-1}$
V	volume	cm^3
W	mass	gm
α	Thermal accommodation coefficient	dimensionless
δ	capture (or sticking) coefficient	dimensionless
ξ	velocity slip coefficient	cm
λ	mean free path	cm

Table of Symbols

μ	coefficient of absolute viscosity	$\text{gm.cm}^{-1}.\text{sec}^{-1}$
ρ	density	gm.cm^{-3}

1. Introduction.

The current interest in space technology has led to the use of large vacuum chambers in applications ranging from low density wind tunnels to space simulation chambers. Regardless of application, the basic objective has been to maintain a very low pressure environment despite, or in conjunction with, a relatively large in-leakage rate of gas. The cryogenic vacuum pumping technique, which consists of freezing gas molecules onto a cold surface and thereby immobilizing them, has been found to be the most practical and economical means of achieving this objective /4/¹.

Information available in the current literature is concerned primarily with determining the pumping rates obtainable from unshielded cryosurfaces. Much of the data is for cryosurfaces in chambers whose dimensions are large compared to the dimension of the cryosurface itself. The in-leakage rates utilized are such that free molecule flow prevails and the thermal resistance of the ice is not a significant factor.

In this thesis, concepts drawn from the kinetic theory of gases will be utilized to examine the significance of mass flow rate, shielding, geometry, and flow regime as design parameters. This will be accomplished by examining low density flow from the standpoint of conductance. A specific objective is to relate these parameters to the prediction of cryogenic vacuum pumping system pressure-flow rate relations.

¹Numbers in / / correspond to references found in the bibliography.

2. Kinetic Theory.

For an understanding of the phenomena associated with low density gas flow, it is necessary to examine the gas microscopically, that is, from the point of view of the kinetic theory of gases. The considerations from the kinetic theory of gases which are applicable to our purpose are: (1) the gas is composed of very small particles or molecules, and (2) these molecules are in constant motion, the motion being intimately related to temperature.

Let us consider the case of a large volume of gas contained in such a way that it is in equilibrium and microscopically at rest. If we could follow an individual molecule in its motion, we would observe it to undergo many changes in velocity as it moves about and collides with other molecules and the walls of the container. At any given moment, therefore, we would expect to find the individual molecules moving in all directions and with great differences in speed. J. C. Maxwell and L. Boltzmann showed that in an equilibrium gas it is possible to determine the way in which the molecular velocities are distributed at any given temperature.

One of the results from the Maxwell-Boltzmann distribution law of immediate concern to us is the value of the mean molecular speed, U_a . This is derived in any of the standard textbooks /24/ dealing with the kinetic theory of gases and is given by the equation,

$$U_a = \left[\frac{8 R_o T}{\pi M} \right]^{\frac{1}{2}} \quad (1)^2$$

We are also interested in knowing the number of molecules which pass

²Numbers in parentheses at right edge of the paper are equation numbers.

through an imaginary plane of area A located in the interior of a volume of gas. Theory /24/ shows that the number of molecules, N, passing through unit area in one direction is

$$N = n \frac{U_a}{4} . \quad (2)$$

It has also been shown /24/ that the molecules crossing the plane in a given time are distributed in direction in accordance with Lambert's or the cosine law.³

Observations of a gas at rest show that the molecules diffuse through the container at a rate much less than their molecular speed. This may be explained by assuming that the molecules do not travel continuously in straight lines but undergo frequent collisions. We may then define a mean free path as the average distance traversed by all the molecules between successive collisions. It has been shown /6/ that the absolute viscosity, μ , is related to the mean free path, λ , by,

$$\mu = C_1 C U_a \lambda . \quad (3)$$

where C_1 is a constant of proportionality. By utilizing the value of the proportionality constant calculated by Chapman /33/, we may express the mean free path as,

$$\lambda = \frac{\mu}{.499 C U_a} . \quad (4)$$

Figure 1 shows the mean free path of nitrogen as a function of pressure and

³Appendix II contains definitions of several terms common to this field.

temperature. The necessary values of viscosity were calculated from Sutherland's relation that,

$$\mu = \frac{K T^{\frac{3}{2}}}{C + T} \quad (5)$$

where for nitrogen, $K = 13.85 \times 10^{-6}$ and $C = 102$.

3. Evaporation and Condensation.

In cryopump design, the primary consideration is the net rate of condensation at the cryopump surface. The net rate of condensation is the absolute condensation rate less the absolute evaporation rate.

Let us consider a cryosurface in contact with an equilibrium gas. Under these conditions, the rate at which molecules strike the surface may be calculated from kinetic theory by means of equation (2). In order to determine the absolute condensation rate, we must make allowance for those molecules which strike the surface but rebound from it without condensing. To account for these molecules, we introduce the sticking (or capture) coefficient δ , which may be defined as the fraction of the colliding molecules which adhere to the cold surface. Therefore, the absolute condensation rate, N , may be expressed as,

$$N' = n \frac{U_a'}{4} \delta'. \quad (6)$$

The significance of the superscript is that the reference is to a surface in contact with an equilibrium gas.

The relation between a condensed phase and its vapor is a kinetic one. Therefore, there is a constant interchange of molecules (and the energy associated with these molecules) between the two mediums. When the condensed phase is in equilibrium with its vapor (that is, the vapor is saturated), absolute evaporation and condensation are going on at equal rates. If the vapor were removed as fast as formed, so as to eliminate condensation entirely, the maximum possible net rate of evaporation would occur. In this case, the net rate of evaporation would be equal to the absolute rate of evaporation. We may calculate this absolute rate of evaporation by utilizing the fact that, when the condensed phase and its vapor are in equilibrium, absolute

evaporation and condensation are going on at equal rates and the rate of condensation can be calculated from kinetic theory as indicated above.

Therefore, the absolute rate of evaporation may be expressed as,

$$N'' = n \frac{U''^a}{4} \delta'' . \quad (7)$$

The significance of this superscript is that the reference is to a condensed phase in equilibrium with its vapor. It should be noted that the applicable pressure in this case is the vapor pressure corresponding to the temperature at the surface of the condensed phase.

4. Flow Regime.

Gas flow characteristics are determined by the relative tendency of the molecules to undergo intermolecular collisions or molecule-wall collisions. It is convenient to consider this tendency by comparing the mean free path to a significant dimension of the flow field. At high pressures, where the mean free path is small compared to a characteristic dimension of the flow field, collisions between molecules occur more frequently than collisions of molecules with the walls. Consequently, intermolecular collisions predominate in determining the characteristic of the flow. For this type of flow, the properties of the gas do not vary appreciably in one mean free path and the gas can be considered a continuous medium. The flow is therefore described and analyzed hydrodynamically and is called continuum or viscous flow. The coefficient of viscosity, which appears in all viscous flow equations, reflects the influence of intermolecular interactions.

At low pressures, the mean free path is large compared to the characteristic dimension and the flow of gas is limited by molecular collisions with the walls. The analysis of the flow is primarily a problem of geometrical nature, and involves determination of the restrictive effect of the walls on the free flight of the molecule. Since there are comparatively few intermolecular collisions, each molecule can be considered to act independently of any others present. Flow under these conditions is therefore called free molecule flow.

Between the limits of viscous flow and free molecule flow there is a region in which both types of collisions must be considered in order to determine the flow characteristics. At the present time there are no analytical expressions which satisfactorily describe the flow over this transitional region. It is therefore necessary to describe the flow in this region by

empirical methods.

In order to define these regimes in terms of measurable quantities, we introduce the Knudsen number. This dimensionless parameter is defined as the ratio of the mean free path to a characteristic dimension. The actual assignment of Knudsen numbers is somewhat arbitrary and depends on the source of information. For our purposes, it is convenient to select the diameter (or hydraulic diameter) as the characteristic dimension and delineate the ranges /18/ as follows:

when $K_n < .01$, the flow is viscous,

when $K_n > 10$, the flow is molecular,

when $.01 < K_n < 10$, the flow is in the transition range.

5. Conductance.

Let us assume a system in which gas flow is taking place under incompressible, isothermal, steady state conditions. In what follows, we will, for convenience, use a flow rate parameter Q defined as the product of the volume flow rate across a plane and the pressure at which this volume flow rate is measured.

Then,

$$Q = P \frac{dV}{dt} . \quad (8)$$

For non-isothermal flow, equation (8) is well defined only when used in conjunction with the perfect gas law,

$$PV = W \frac{R_o}{M} T . \quad (9)$$

By differentiation,

$$P \frac{dV}{dt} = \frac{dW}{dt} \frac{R_o}{M} T , \quad (10)$$

and we see that the flow rate parameter Q is a constant for the case of isothermal flow. For the case of non-isothermal flow, it is convenient to relate Q to the mass flow rate G by the equation,

$$G = \frac{Q}{\frac{R_o}{M} T} . \quad (11)$$

Now, let us define conductance F as,

$$F = \frac{Q}{(P_1 - P_2)} , \quad (12)$$

where $P_1 - P_2$ is the driving pressure. It is seen that this quantity is proportional to the mass rate of flow per unit difference of pressure.

(a) Molecular Flow

The theoretical manner of attacking the problem of flow in this range and the first experimental verification of the theory are due to Knudsen /35/. A brief discussion of Knudsen's work and the derivation of his basic formula for the case of a long tube is contained in reference /24/.

For the case of a long, circular tube the rate of flow is

$$Q = \frac{2}{3} \frac{r^3}{L} U_a (P_1 - P_2). \quad (13)$$

Therefore, the conductance for this case is

$$F_t = \frac{2}{3} \frac{r^3}{L} U_a. \quad (14)$$

Let us consider the conductance of an orifice. In the section on kinetic theory of gases, it is noted that the rate at which molecules pass (in one direction) through a plane located in the interior of an equilibrium gas is

$$N = n \frac{U_a}{4} A.$$

This leads us to the conclusion that

$$Q = \frac{U_a}{4} A (P_1 - P_2). \quad (15)$$

The significant restriction on this formula is that the flow area, A , must be small compared to both the mean free path of the gas and the 'container' since the derivation is based on an equilibrium gas. If we consider this plane to be an aperture, we see that the conductance of an orifice may be expressed as,

$$F_o = \frac{U_a}{4} A . \quad (16)$$

It may be shown /11/ that for the case of an orifice located in a diaphragm across the exit of a tube, the effective conductance of the orifice may be related to F_o by the relation,

$$F_{eff} = \frac{1}{1 - \frac{A_o}{A}} F_o \quad (17)$$

where A_o is the area of the orifice and A is the cross-sectional area of the tube.

From a detailed investigation, P. Clausing /36/ related the conductance of a circular tube to the conductance F_o of an orifice of equal area by means of a factor known as Clausing's K factor. A plot of Clausing's K factor versus the length to radius ratio is shown in Figure 2.

The significance of the term "long" used in connection with cylindrical tubes, is that the tube must be of such length that end corrections are negligible. The effect of neglecting end corrections may be determined by comparing the ratio of the conductance as computed by the long tube formula to the true conductance as determined by Clausing. A plot of this ratio as a function of length to radius ratio is shown in Figure 3.

Data for a variety of configurations has been presented by several authors /16/, /34/ in a form similar to that used by Clausing. The simplicity of the conductance relationships in the free molecule flow regime is one of the great advantages of this system of analysis.

(b) Viscous Flow

Under the limitations as noted above, we may express the flow rate through a long circular tube by Poiseuille's equation,

$$Q = \frac{r^4}{8 \mu L} P_a (P_1 - P_2) \quad (18)$$

where,

$$P_a = \frac{P_1 + P_2}{2} \quad (19)$$

By equation (12), the conductance F_v for this case is,

$$F_v = \frac{r^4}{8 \mu L} P_a \quad (20)$$

The significance of the tube being described as long is that, in this case, entrance phenomena may be neglected. Viscous flow entrance effects will be ignored except to note that their effect is to lower the flow rate for a given pressure difference below the value predicted by equation (18).

(c) Transition Flow

The information available in the current literature on this subject is apparently restricted to an empirical relation formulated by Knudsen. As a result of a series of measurements of flow in long tubes, Knudsen deduced that the conductance can be expressed as,

$$F = F_t \left[\frac{F_v}{F_t} + Z \right] \quad (21)$$

where F_v is the conductance of a long tube in the viscous flow regime and F_t is the conductance of a long tube in the molecular flow regime.

Knudsen's expression for Z is,

$$Z = \frac{1 + \frac{d}{\mu} \frac{M}{R_o T} P_a}{1 + 1.24 \frac{d}{\mu} \frac{M}{R_o T} P_a} \quad (22)$$

By utilizing the kinetic theory relation for viscosity, equation (22) can be written as,

$$Z = \frac{1 + \frac{1.254}{K_n}}{1 + \frac{1.548}{K_n}} \quad (23)$$

By substitution of equations (23), (20), (14), and (3) into equation (18) and rearranging, we obtain

$$\frac{F}{F_t} = \frac{.0736}{K_n} + \frac{1 + \frac{1.254}{K_n}}{1 + \frac{1.548}{K_n}} \quad (24)$$

F/F_t as a function of K_n is shown in Figure 3.

For the purpose of this thesis it is necessary to predict the variation of conductance with flow regime for various configurations. The remarks which follow give an indication of some of the concepts involved.

We have previously mentioned that our discussion will be concerned with flow regime. In order to simplify our remarks, we relate flow regime to Knudsen number and in turn relate Knudsen number to the determination of an appropriate characteristic dimension.

We also note that our flow may be either internal flow (as flow in a long tube) or submerged flow (a cryosurface is normally "submerged" in the condensable gas). In order to compare these situations, it is advantageous to use one type of a dimension. This is done by utilizing a pseudo-hydraulic diameter for the case of submerged flow. This hydraulic diameter is defined by considering the largest projected area of any three dimensional figure as a flow area and then calculating the hydraulic diameter by the

usual method.

We will limit our discussion to characteristics of orifices and long tubes since the characteristics of any other configuration should fall between these two.

Let us first consider the case of the long tube. By examining Knudsen's expression for the variation of conductance as a function of Knudsen number, we see that:

(1) The characteristic dimension is proportional to the tube diameter.

(2) The complete transition from free molecule flow to viscous flow occurs over a range of Knudsen numbers of approximately two orders of magnitude.

The case is now considered of a cryosurface in a container whose dimensions are large compared to the cryosurface dimensions. In this situation, the cryosurface can be considered submerged and we use a pseudo-hydraulic diameter as previously defined. We first note that the cryosurface is considered to be in free molecule flow only so long as equation (2) applies. Alternatively, the cryosurface is in the free molecule regime only so long as there is no bulk motion toward it. In connection with this, we note that bulk motion toward the cryosurface will occur when the absence of collisions, due to the lost molecules, becomes significant. From what has been stated above, it seems reasonable to conclude that:

1) Since the rate at which molecules are lost is proportional to the area, the characteristic dimension for predicting transition is probably a function of the square of the pseudo-hydraulic diameter.

2) If the characteristic dimension is considered in this light, the complete transition from free molecule flow to viscous flow probably

occurs over a range of Knudsen numbers of approximately two orders of magnitude.

3) Since the effective area of a cryosurface is a function of the sticking coefficient, it must be taken into account in determining transitional behavior.

(d) Cryosurface Conductance

This section will be devoted to the case of a cryosurface located in a chamber whose dimensions are large compared to the dimensions of the cryosurface itself.

1) Free Molecule Flow. From a consideration of the remarks made in Section 3, we deduce that the net molecule flow rate to a cryosurface in the free molecule flow regime may be expressed as the difference between N' (equation 6) and N'' (equation 7). If we use the subscript s to designate the surface condition and the subscript i to denote conditions in the surrounding medium, we see that the conductance of a cryosurface for this case may be expressed as,

$$F = \frac{A \left[\frac{R_o T_i}{2 \pi M} \right]^{\frac{1}{2}} \left[\sigma_i P_i - \sigma_s \sqrt{\frac{T_s}{T_i}} P_s \right]}{P_i - P_s} \quad (25)$$

Since a cryosurface may be likened to an orifice, the remarks concerning orifices in Section 5(a) will apply to a cryosurface.

2) Viscous Flow Regime. Although no information pertaining to this regime is available in the literature, orifice flow theory leads us to assume that mass motion toward the cryosurface could, at most, occur at the sonic velocity.

3) Transition Regime. It will be assumed that the velocity

of mass motion toward the cryosurface varies linearly between the free molecule and viscous regimes.

6. Discussion of Parameters Influencing Cryogenic Vacuum System Design.

Since the object of the cryopumping system is to maintain a low pressure in conjunction with large in-leakage rates, we are primarily interested in determining the effect of all other parameters on the pressure. Our first consideration is the vapor pressure of the condensed phase since this pressure fixes the lowest pressure which the system can attain. In the remaining discussion, we assume that the solid phase will remain attached to the cryosurface. Most of the experimental evidence available indicates that this is the case. Under high mass flow rates, however, the condensed solid may have a tendency to flake off /18/.

Figure 4 shows the vapor pressure of solid nitrogen as a function of saturation temperature. An examination of Figure 4 reveals two significant factors. One of these is that in order to obtain a low pressure it is necessary that the cryosurface temperature also be correspondingly low. The cryosurface temperature, in turn, is fixed by the temperature of the coolant. Since the rate at which heat can be removed by the cryogenic refrigeration system decreases as the coolant temperature is lowered, it is essential that the heat load on the cryopump be as small as possible. When we consider that the desired cryopump temperature is approximately 20 to 30 degrees Kelvin, we immediately see that radiation shielding is required in order to minimize the radiation heat load on the cryopump from the surrounding environment. Since the heat load, due to the condensing gas, is a direct function of temperature (for example, see Figure 5 for Nitrogen), it may also be necessary to pre-cool the gas before admitting it to the cryopump.

Figure 4 also shows that a small change in temperature will result in

a large pressure change. This indicates, that at relatively large in-leakage rates, factors which affect the surface temperature of the solid phase may be significant design parameters. At time zero, imagine the cryo-pump to consist of a bare cold wall at some fixed temperature. At some later time, a certain mass of gas has condensed on this wall resulting in a build-up of the condensed solid. This solid represents a significant resistance to heat flow, the magnitude of this resistance being determined by the thickness of the solid. Therefore, we can see that the rate of change of thermal resistance is directly proportional to the mass rate of flow and to the area of the condensing surface. If the coolant temperature is considered fixed, we see that the temperature at the surface of the solid depends on the rate of heat flow through the solid. This heat transfer is made up of three components; namely, (1) radiation, (2) heat of vaporization, and (3) sensible heat above saturation conditions. If radiation is not a significant factor, we see that the surface temperature is directly related to the temperature of the gas and its mass flow rate to the cryosurface. This relationship is illustrated by Figure 6.

Let us now consider the pressure adjacent to the cryosurface. Geometrical considerations (in the sense of the relative dimensions of the cryosurface and surroundings) are significant so we will first consider the case where the cryosurface is "small" compared to the containing vessel. The conductance of the cryosurface for this case is given by equation (25).

Since we are interested in a driving pressure, equation (25) will be more meaningful if expressed in a mass flow rate form. In terms of mass rate of flow, equation (25) is

$$G = 5.833 \times 10^{-5} \left[\frac{M}{T_i} \right]^{\frac{1}{2}} \left[\sigma_i P_i - \sigma_s \sqrt{\frac{T_i}{T_s}} P_s \right] A \quad (26)$$

or, in terms of P_i ,

$$P_i = \frac{1}{\sigma_i} \left[\frac{G \sqrt{\frac{T_i}{M}}}{5.833 \times 10^{-5} A} + \sigma_s \sqrt{\frac{T_i}{T_s}} P_s \right] \quad (27)$$

It will be recalled that the sticking coefficient σ_s is associated with a condensed phase in equilibrium with its vapor. Since experimental evidence /1/ indicates that the sticking coefficient under these conditions is nearly equal to one, σ_s will be assumed equal to one in the following considerations.

We see that in order to minimize the driving pressure, it is desirable to increase the sticking coefficient σ_i and conductance area A and decrease the inlet gas temperature T_i . Depending on the surface temperature and inflow rate, the spontaneous emission of cold molecules from the surface of the condensed phase may result in cooling the incoming gas so that the cryopump will in effect see a lower temperature than T_i .

Now, consider the sticking coefficient σ_i . It has been determined /5/ that the sticking coefficient is approximately 0.6 for cryopumping 300 degrees Kelvin carbon dioxide on a smooth sphere. If fins were installed on the sphere, a molecule would tend to make multiple collisions before escaping from the cryopump and the effective sticking coefficient would be

increased. In connection with adding fins to a cryosurface, it should be noted that so long as the mean free path is large compared to the cryosurface dimensions, the effective conductance area will be the area of an "envelope" surrounding the extremities of the fins rather than the actual surface area.

Let us now consider the effect of geometry on the system. One possibility is that the cryosurface dimensions are of comparable size to the flow channel leading to it. An example of this might be a cryosurface located at the end of a long tube. For this case, equation (17) applies and we note that the significant conductance is that of the tube only.

A second possibility is that the cryosurface may be located very close to an obstruction such as a radiation shield. This problem is especially applicable for the type of construction used in space simulation chambers. Conductance procedures do not apply to this problem in the free molecule flow regime and they must be solved by either Monte Carlo analysis or by radiation view factors.

We are now ready to consider the time factor. As time passes, the increasing thickness of the ice layer on the cryosurface is continually raising the downstream pressure. This will force flow conditions toward the transition regime. However, if the flow rates are small, the time involved may be so long that it does not become a significant factor for any given run. This condition means that provisions for defrosting the pumping system should be made. Since the ice thickness is related to the effective condensing area, we must determine what area to use. It is felt that setting the condensing area equal to the envelope area is probably good design practice.

Up to this point our assumptions have been based on the premise that all of the gases present are condensable. This generally will not be true since at a surface temperature of 30 degrees Kelvin, any Helium, Hydrogen or Neon present will not be condensed. This means that pockets where non-condensables may collect should be eliminated. It also means that our design must allow for a free flow path to some other pumping apparatus whose function will be to remove the non-condensables.

Cryopumping involves some surface phenomena which are dealt with here only as a matter of interest. Two examples are "bare surface effect" /5/ and "trapping effect" /5/. In the case of the bare surface effect, it has been noted that the sticking coefficient is very low and increases gradually to some constant or nearly constant value as the surface becomes coated with ice. This phenomenon is consistent with condensation theory. It has been noticed in the trapping effect that some condensed phases have the ability to trap molecules at the surface and perhaps reduce absolute evaporation from the surface. Water vapor apparently will even trap some non-condensables. The trapping effect is of particular interest in large space simulation chambers.

7. Conclusions.

Cryogenic vacuum pumping techniques are being used in applications where the flow regime ranges from free molecule (space simulation chambers) to wind tunnels operating in the continuum regime. The concept of conductance is the only method presently available for analyzing the significant parameters throughout this range. Conclusions based on this concept are.

1) The conductance relations indicate that conductance increases as the flow regime moves from free molecule to continuum flow. The extremely low conductance in the free molecule flow regime is particularly significant and is a major factor in the design of low density flow systems. In this respect, a cryopump has a significant advantage over conventional pumping systems in that it may be mounted directly inside the vacuum chamber, thereby reducing total system conductance to a minimum.

2) Cryogenic pumping design is basically a balance between reducing the heat load on the cryopump and optimizing the conductance of the system. This is particularly true in low density wind tunnel applications.

3) Radiation shields are required for the economical utilization of the cryogenic pumping system.

4) The addition of fins to cryopumping surfaces increases their performance by raising the capture coefficient.

5) The maximum benefit to be derived from the use of fins occurs when the non-condensable input is very small.

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APPENDIX I

Figure		Page
1.	Mean Free Path of Nitrogen	27
2.	Value of Clausing's K Factor	28
3.	Ratio of Long Tube Conductance to True Conductance as a Function of Length to Radius Ratio	29
4.	Ratio of Actual Conductance to the Molecular Flow Conductance for Long Tubes as a Function of Knudsen Number	30
5.	Vapor Pressure of Solid Nitrogen	31
6.	Total Enthalpy as a Function of Temperature for Nitrogen	32
7.	Heat Transfer Rate for Nitrogen as a Function of Mass Flow Rate and Gas Temperature	33

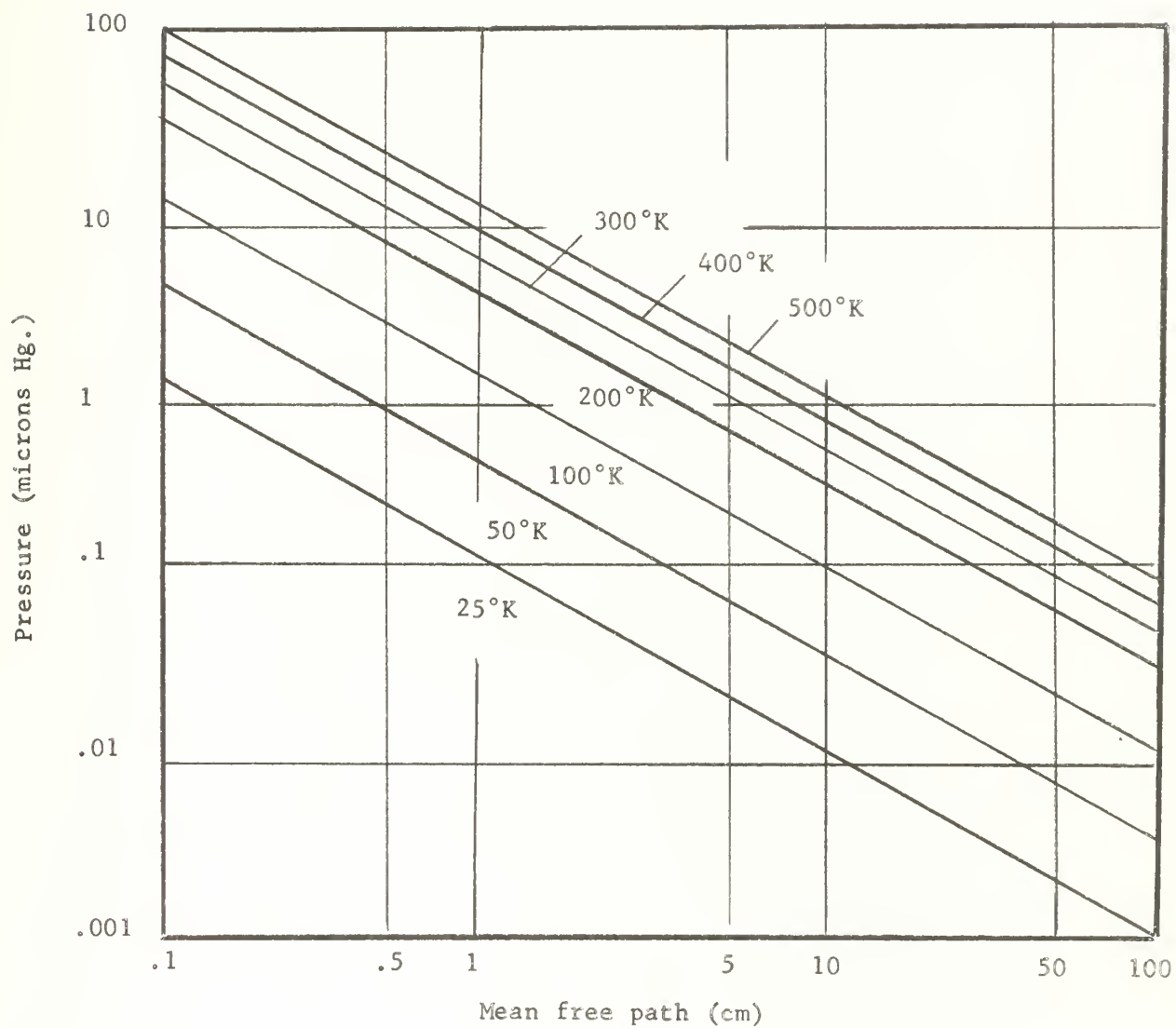


Fig. 1. Mean free path of Nitrogen.

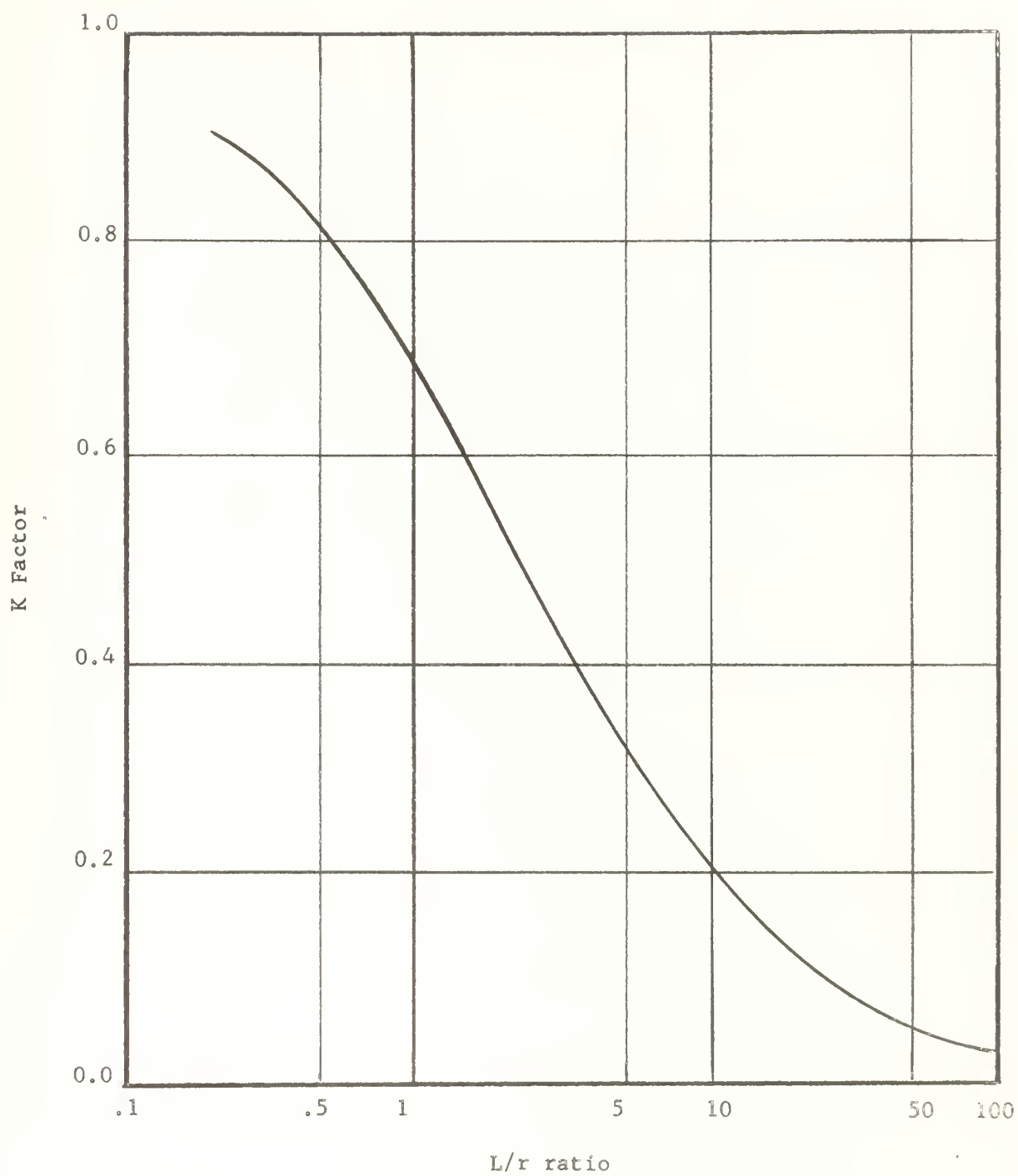


Fig. 2. Value of Clausing's K factor.

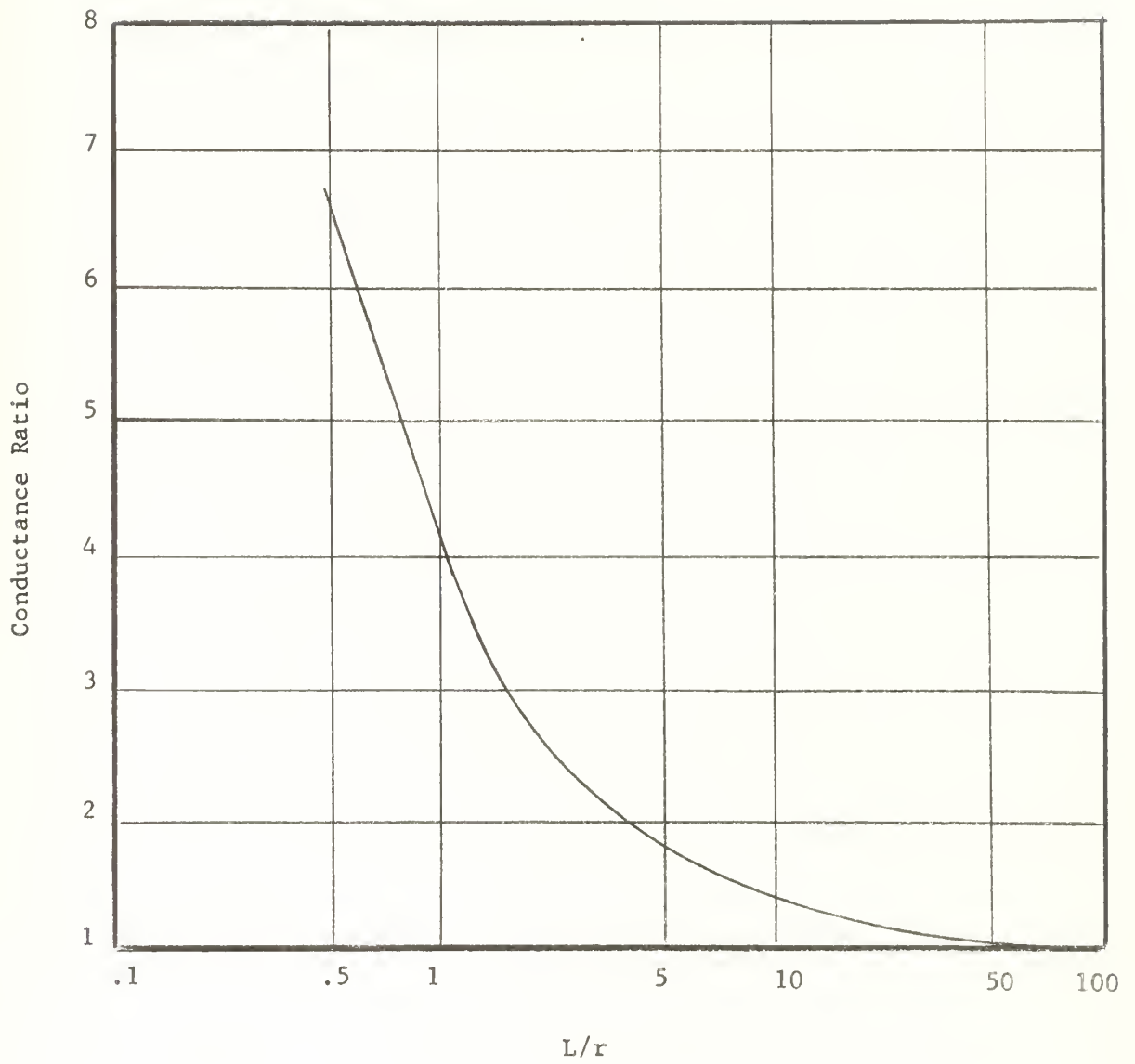


Fig. 3. Ratio of long tube conductance to true conductance as a function of length to radius ratio.

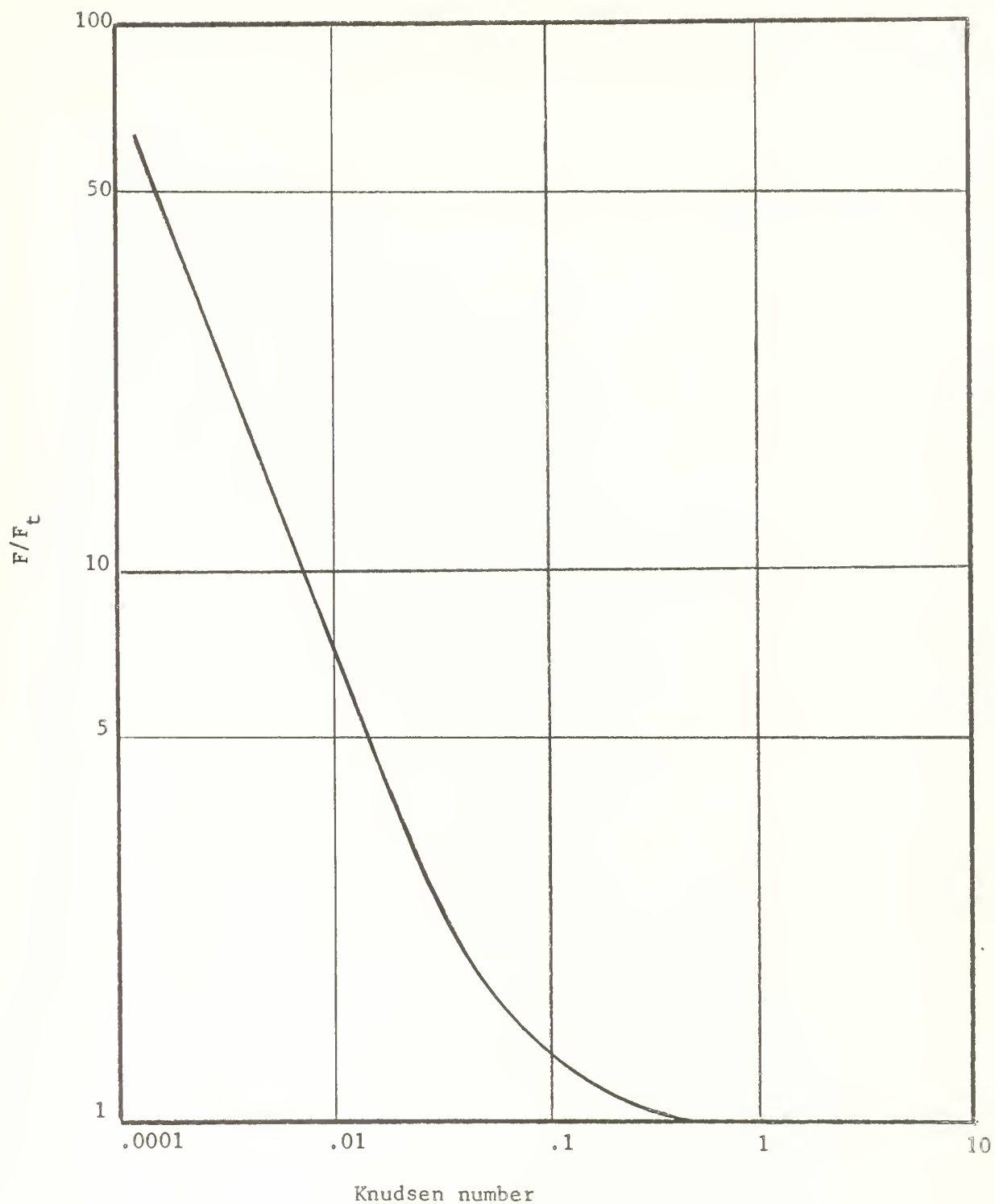


Fig. 4. Ratio of actual conductance to the molecular flow conductance for long tubes as a function of Knudsen number.

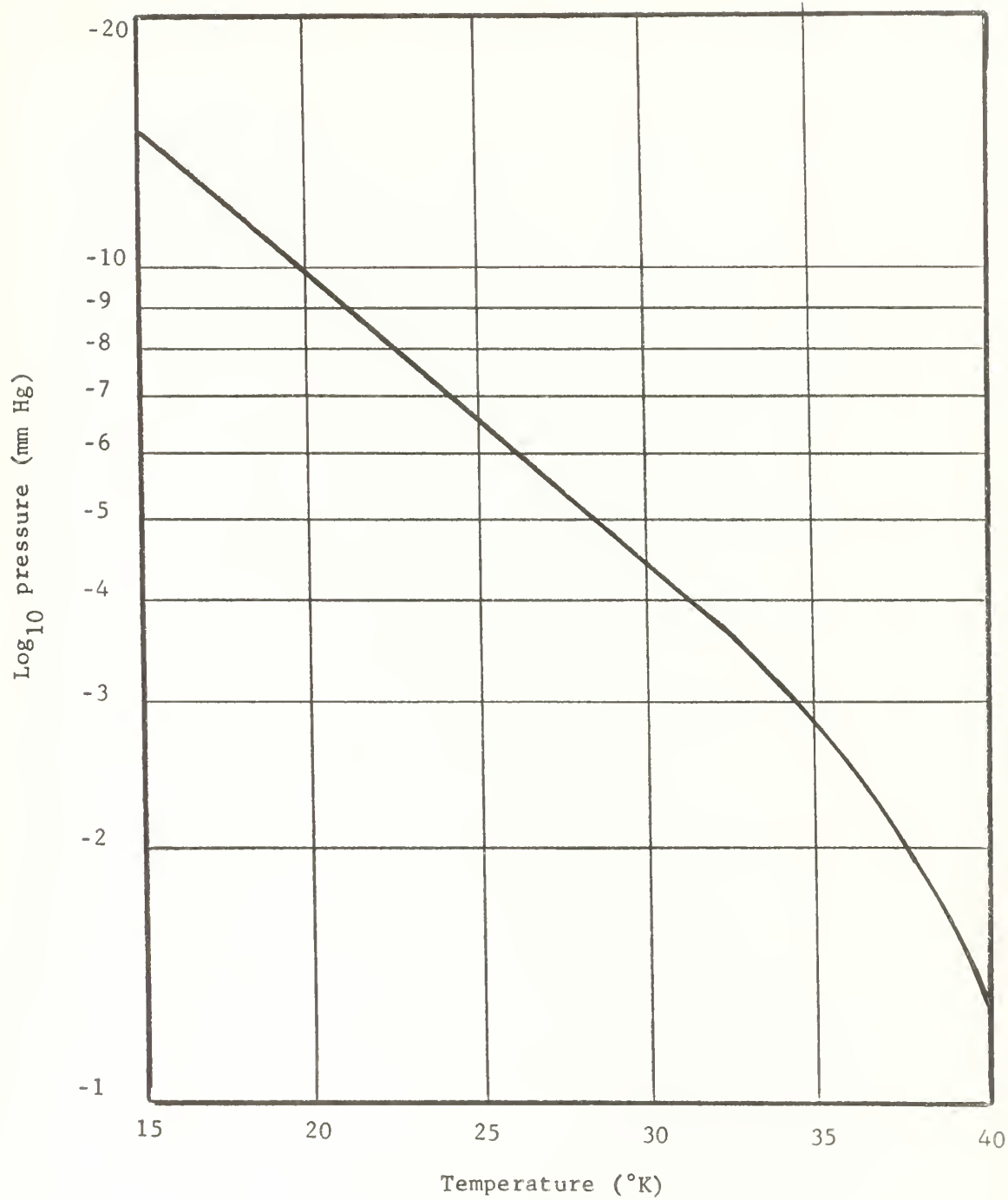


Fig. 5. Vapor pressure of solid Nitrogen.

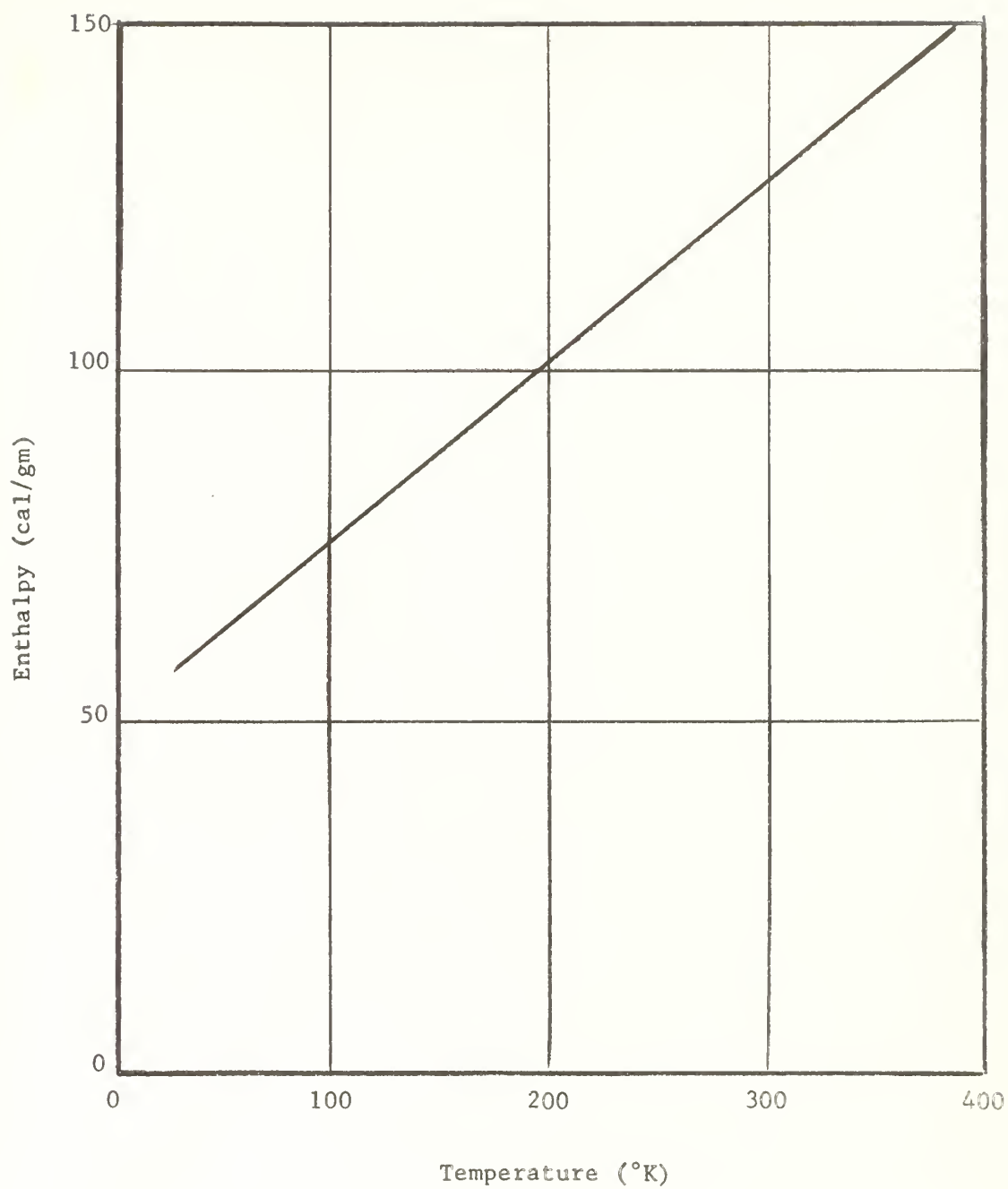


Fig. 6. Total enthalpy as a function of temperature for Nitrogen.

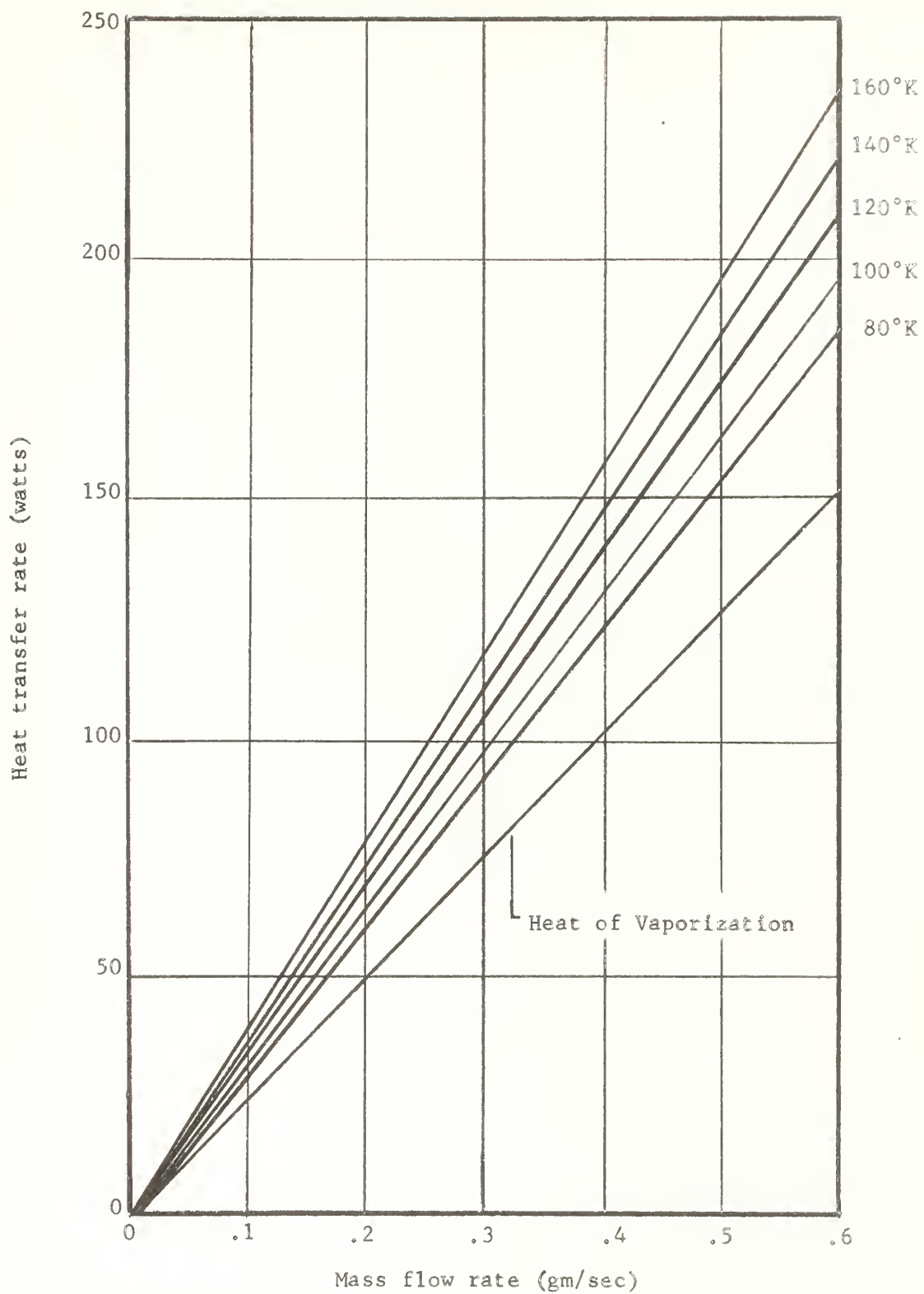


Fig. 7. Heat transfer rate for Nitrogen condensing at 25°K as a function of mass flow rate and gas temperature.

APPENDIX II

Glossary

Slip Flow Regime: As the density of a flowing gas is lowered to a point where all collisions other than intermolecular ones can no longer be neglected, it is observed that the gas begins to 'slip' over the wall. Flow in which this occurs is known as viscous flow with slip, or more commonly, slip flow. It occupies a portion of the transition regime as defined in this paper.

Slip Coefficient: The degree of slip is expressed by a constant called the slip coefficient. The slip coefficient may be defined as the ratio of the slip velocity to the velocity gradient at the wall /24/.

Specular reflection: A molecule is said to reflect specularly when the tangential velocity component is conserved and the normal velocity component undergoes a reversal in direction but no change in magnitude. In other words, the reflection is a perfectly elastic one, such as a ball bounding from a smooth, hard surface.

Diffuse reflection: A molecule is said to reflect diffusely when the ultimate direction of reflection is independent of the incident direction of a given molecule. Diffuse reflections are normally considered to obey Lambert's cosine law.

Lambert's Cosine Law: The probability of a molecule leaving the surface in any given direction is proportional to the cosine of the angle of that direction to the normal to the surface.

Maxwell's Reflection Coefficient: This ratio expresses the fraction of tangential momentum which a molecule gives to a surface upon striking it. By considerations of the kinetic theory of gases /24/, Maxwell's reflection

coefficient may be related to the slip coefficient by the following formula.

$$\zeta = 2 \left[\frac{2-f}{f} \right] \lambda$$

f may be interpreted as the fraction of the incident molecules that are reflected diffusely from the surface, the rest being reflected specularly.

Maxwell's Reflection Coefficient, f

Gas	Surface	f	Reference
Air	Oil	0.90	/29/
He	Oil	0.87	"
H ₂	Oil	0.93	"
CO ₂	Oil	0.92	"
Air	Hg	1.00	"
Air	Machined Brass	1.00	"
He	Polished Ag ₂ O	1.00	/30/
H ₂	Polished Ag ₂ O	1.00	"
O ₂	Polished Ag ₂ O	0.99	"
Air	Polished Ag ₂ O	0.98	"

Accommodation Coefficient: (Thermal Accommodation Coefficient)

When a molecule strikes a wall, we would not expect a complete interchange of energy to occur on the first collision. In fact, it may take many collisions for this to occur. Therefore, Knudsen introduced the accommodation coefficient to indicate the extent to which molecules that are reflected from a surface have their mean energy adjusted or accommodated toward what it would be if the returning molecule were issued out of a Maxwellian

gas at the temperature of the wall. The accommodation coefficient may, therefore, be defined either in terms of energy as,

$$\alpha = \frac{E_i - E_r}{E_i - E_s}$$

or, by assuming the accommodation coefficient to have the same value for the internal molecular energy that it has for the translatory energy, in terms of temperature as,

$$\alpha = \frac{T_i - T_r}{T_i - T_s}$$

where the subscript i stands for incident, the subscript s for surface, and the subscript r for the actual state of the reflected molecule. At other than high temperature the two expressions are equivalent /24/.

Representative values of the accommodation coefficient are included in the following table for air.

Accommodation Coefficient for Air

Type of Surface	Value of α
Machined Aluminum	0.95 - 0.97
Etched Bronze	0.93 - 0.95
Polished Bronze	0.91 - 0.94
Etched Aluminum	0.89 - 0.97
Etched Cast Iron	0.89 - 0.96
Machined Bronze	0.89 - 0.93
Flat Laquer on Bronze	0.88 - 0.89
Polished Aluminum	0.87 - 0.95
Polished Cast Iron	0.87 - 0.93
Machined Cast Iron	0.87 - 0.88

We would expect that the thermal accommodation coefficient would be different for translational, rotational and vibrational molecular energies. However, experimental evidence seems to indicate that one coefficient is generally sufficient /6/.

Maxwellian Gas: A Maxwellian gas is a gas whose molecular velocities are distributed in accordance with the Maxwell-Boltzmann distribution laws.

Pumping Speed: The speed of a pump, S, is defined /1/ by the relation,

$$- \frac{dP}{dt} = \frac{S}{C} (P - P_s),$$

where P_s is the attainable vacuum and C the volume to be exhausted. S has the units of conductance and is quoted frequently in liters per second. We may also define

$$E = S \left(1 - \frac{P_s}{P}\right)$$

so that

$$- \frac{dP}{dt} = \frac{E}{C}$$

and E is the actual rate of exhaust at any instant. Thus, E varies from values approximately equal to S at large values of P to zero at $P = P_s$. The value of S then drops with time to a zero value when the attainable vacuum has been reached.

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An evaluation of cryogenic vacuum system



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